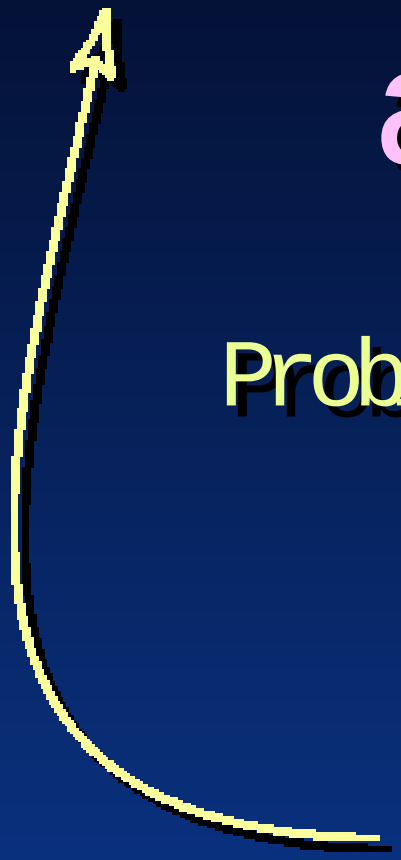
Hard QCD Spin Physics at Brookhaven



Probing QCD from the inside out

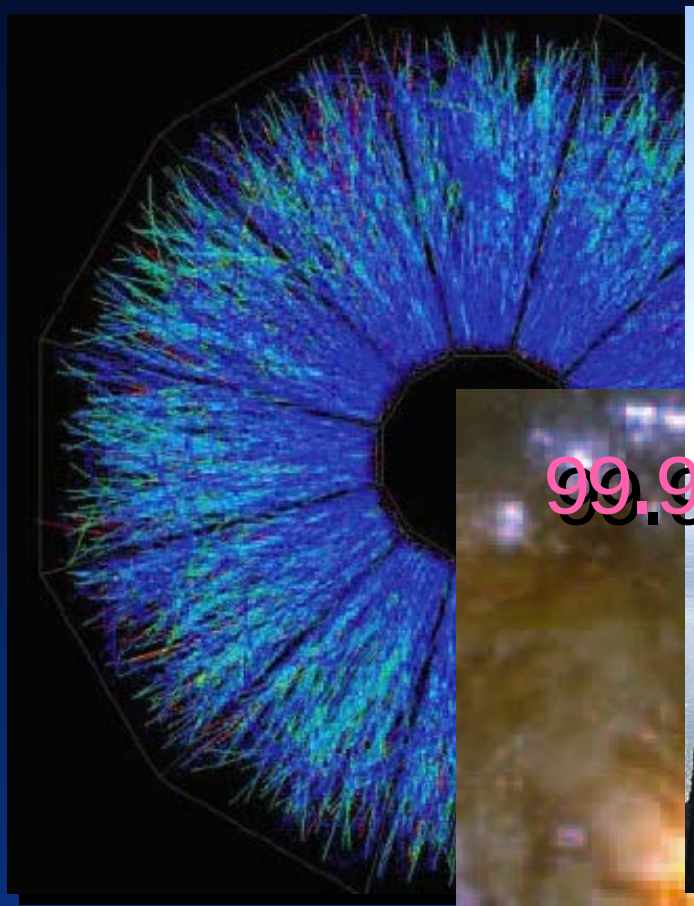
Deep Inelastic
&
Difficult!

R. L. Jaffe

NSAC, April 4, 2005

- RHIC is the world's unique polarized pp-collider
- After a long, extremely challenging technical development process, RHIC is poised to provide answers to some of the most important questions in hadron structure.
- The first large data sets will be obtained in the 2005-2007 time frame. 500 GeV data adds great value.
- The questions have attracted worldwide attention, but only RHIC can answer them (there is no comparable program at LHC or any other facility --- if the work is not done at RHIC, the questions will not be answered)

$$\mathcal{L} = -\frac{1}{4}\mathrm{Tr}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} + \bar{\mathbf{q}}(\mathbf{i}\mathbf{D}_{\mu}\gamma^{\mu} + \mathbf{m})\mathbf{q}$$



99.99% of the visible universe

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Why study QCD?

Lagrangian, lattice?

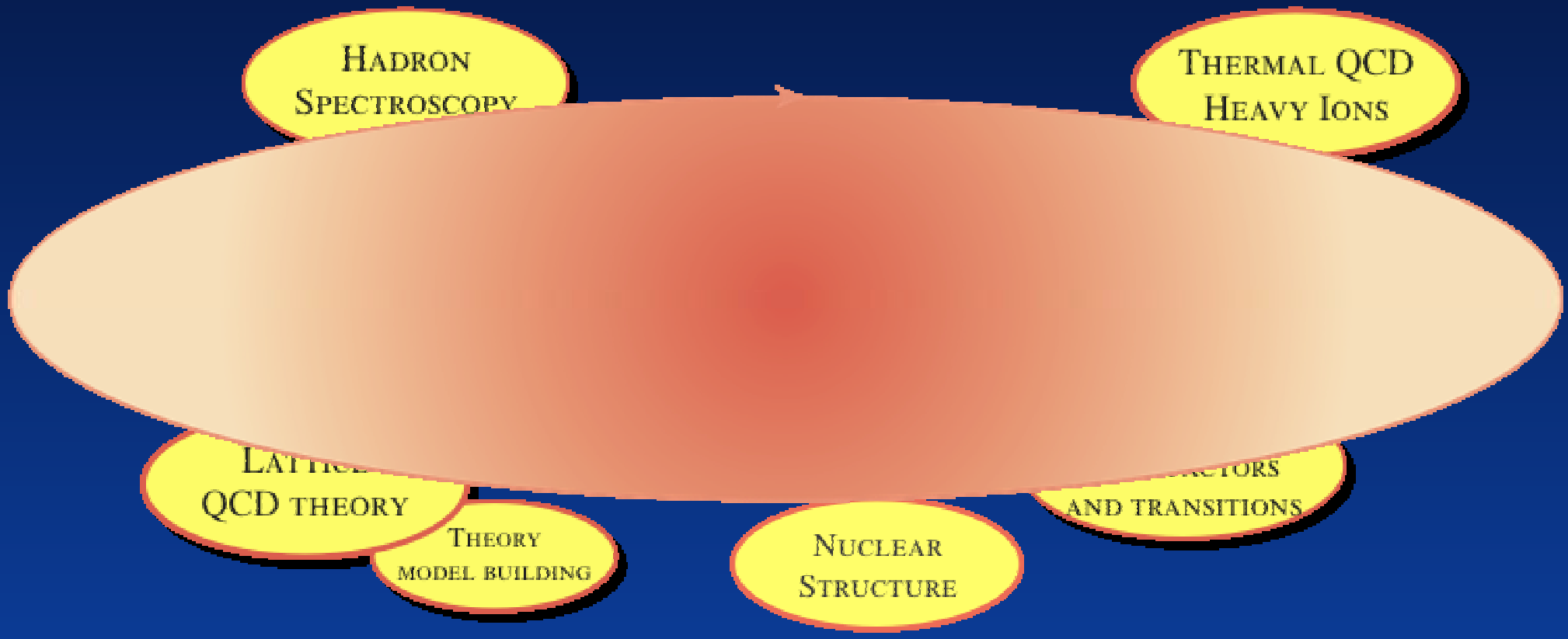
- Perfect
  - No parameters (for "light quarks")
  - All interactions from symmetries
  - Warm up for the mother of all theories
- All QCD phenomena are emergent
  - Mass(!), hadrons, chiral symmetry breaking, constituent quarks, vector dominance...
  - Exactly what we understand least in fundamental physics
- Far from understood --- unsolved puzzles & haunting regularities

What's the point?

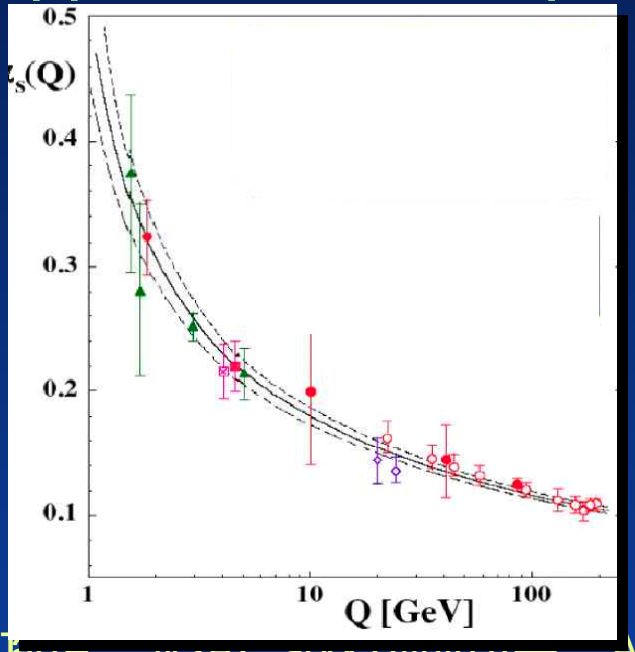
Lagrangian, lattice?

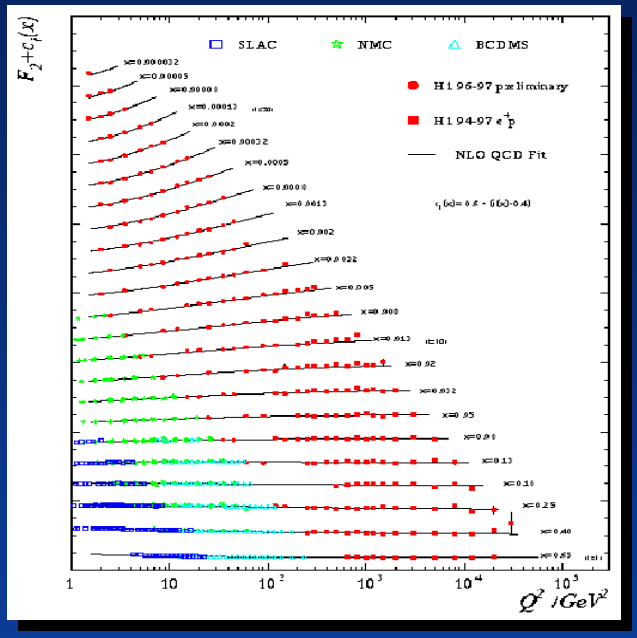
To obtain an analytic, phenomenological, powerful, understanding of QCD in the confining domain.

Links to other core NP objectives



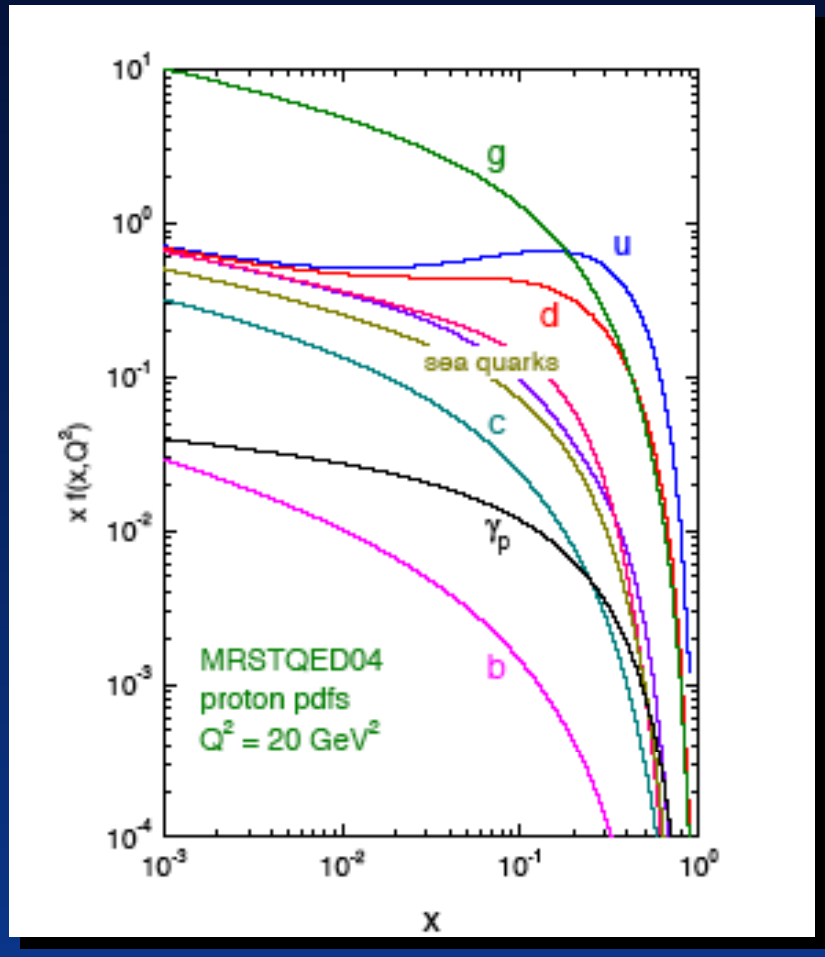
- No "wavefunction" for the nucleon
- No Schroedinger equation for time evolution
- No perturbative expansion for hadrons
- Asymptotic freedom at short distances
- Complete control from renormalization group
- Suppression of complexity through the twist expansion





Everything we know about the nucleon beyond static moments comes from deep inelastic processes

- Quark distributions
- Antiquark distributions
- Gluon distribution



Fundamental quantitative tests of QCD

- Baryon number (GLS) sum rule

$$\int_0^1 dx \left((F_3^{\nu p}(x) + F_3^{\bar{\nu} p}(x)) \right) = 3$$

- Bjorken sum rule

$$\int_0^1 dx \left((g_1^{ep}(x) - g_1^{en}(x)) \right) = \frac{1}{6} \frac{g_A}{g_V}$$

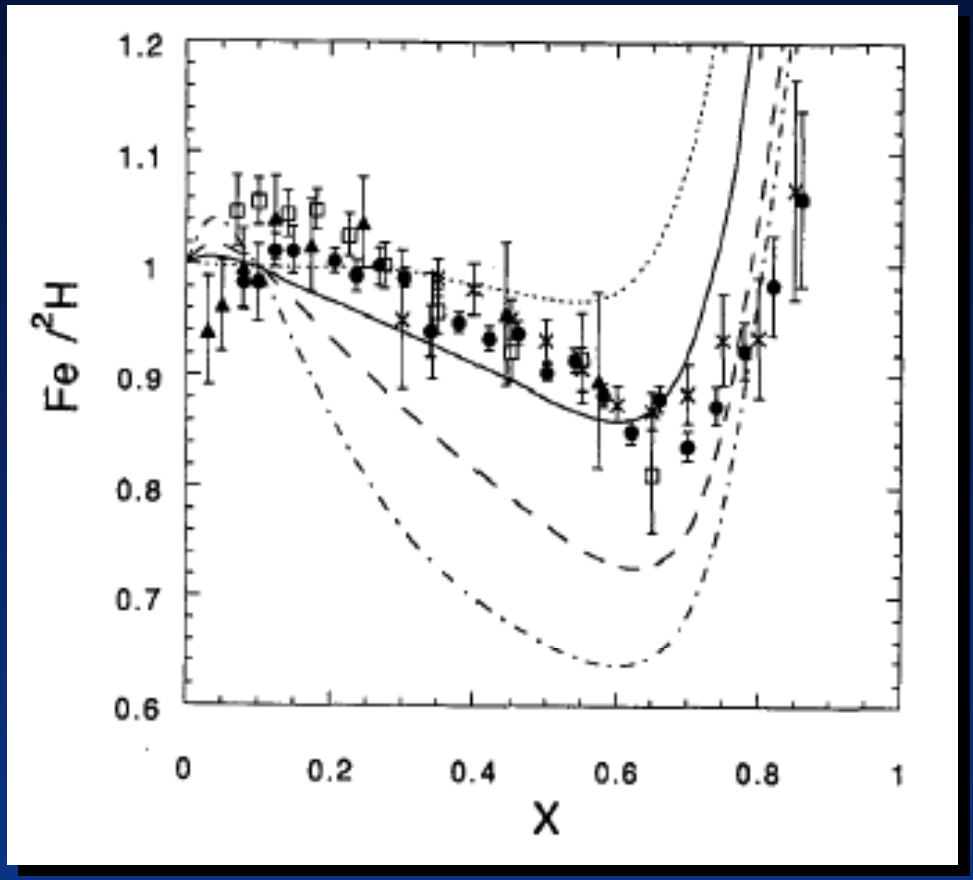
$$\begin{aligned} \int_0^1 dx\, g_1^{\mathrm{cp-cn}}(x,Q^2) &= \frac{1}{6}\frac{g_A}{g_V}\left\{1 - \frac{\alpha_s}{\pi} - \frac{43}{12}\frac{\alpha_s^2}{\pi^2} - 20.215\frac{\alpha_s^3}{\pi^3}\right\} \\ &+ \frac{M^2}{Q^2}\int_0^1 dx\, x^2 \left\{\frac{2}{9} g_1^{\mathrm{cp-cn}}(x,Q^2) + \frac{1}{6} g_2^{\mathrm{cp-cn}}(x,Q^2)\right\} - \frac{1}{Q^2}\frac{4}{27}\mathcal{F}^{\mathrm{u-d}}(Q^2) \end{aligned}$$

A History of Surprises

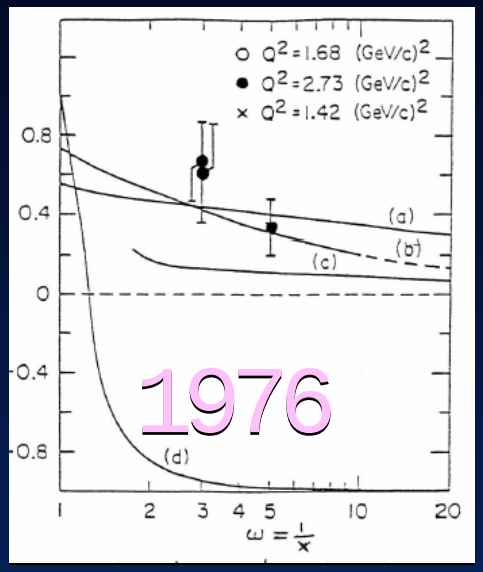
- Half the proton's momentum is carried by gluons

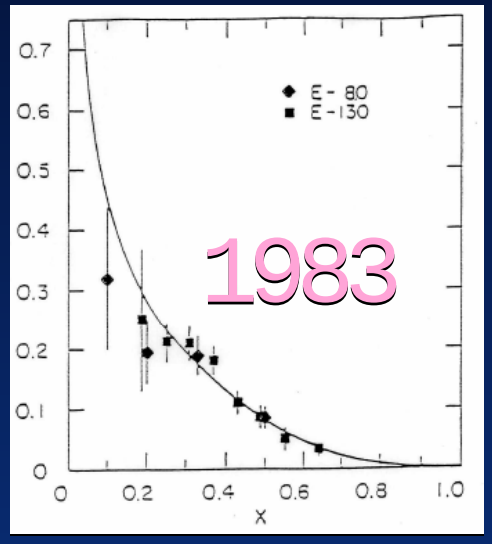
- Quarks in nuclei are partially deconfined (EMC effect)

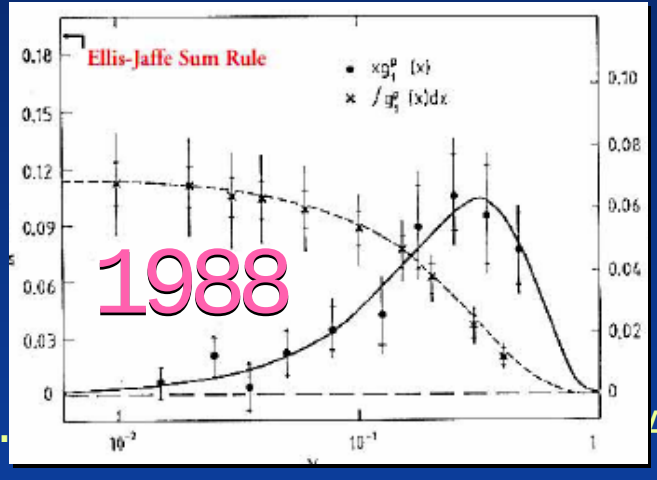
- And, of course, the proton spin puzzle

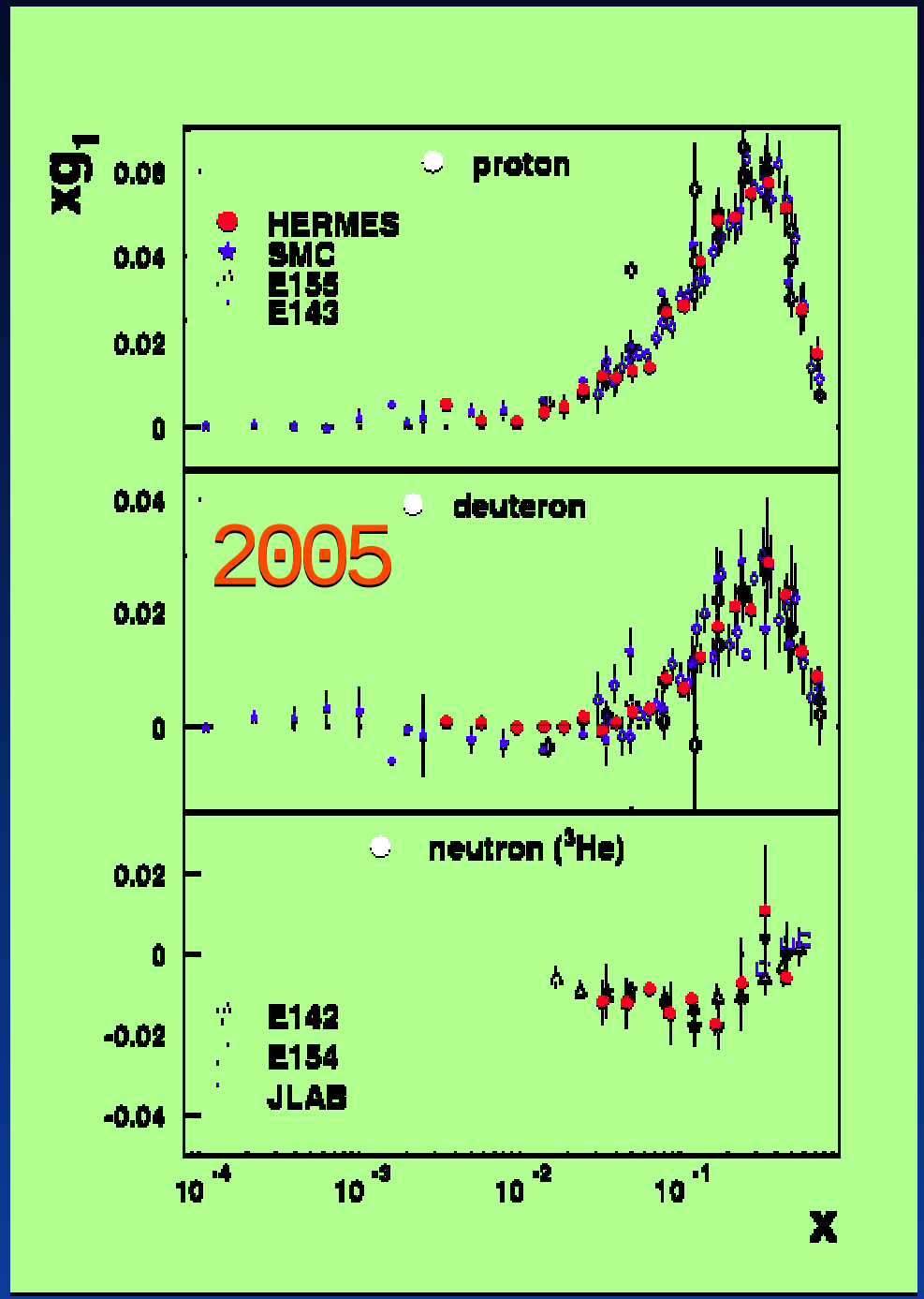


Polarized deep inelastic electron scattering



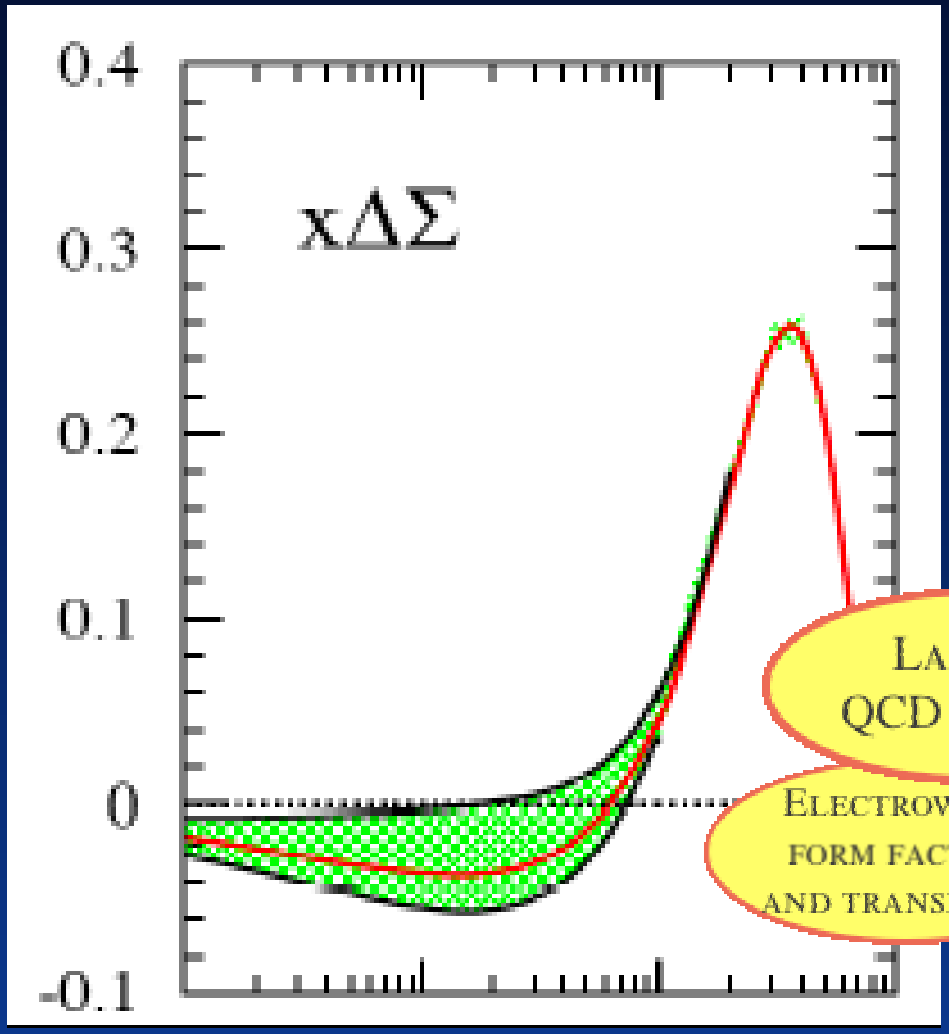






Spin surprise

$$\Delta\Sigma(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$



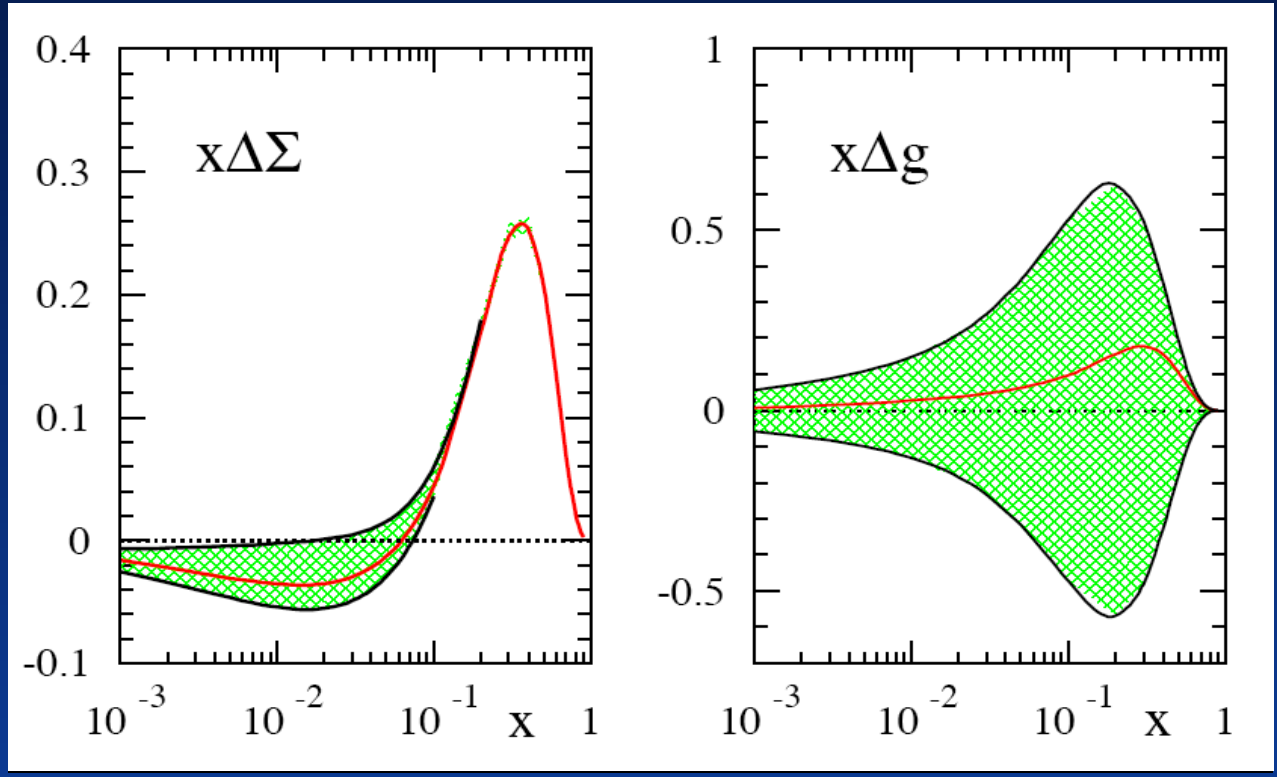
Only a small fraction of the proton's spin is carried by the spin of the quarks

$$14 \pm 9 \pm 21\%$$

Parsing the nucleon spin

$$\frac{1}{2} = \int_0^1 dx \left[\frac{1}{2}\Delta\Sigma(x,Q^2) + \Delta g(x,Q^2) + \mathcal{L}_Q(x,Q^2) + \mathcal{L}_G(x,Q^2) \right]$$

Glue by evolution



Gluon spin in the nucleon -- a world class problem

- Initial response --- use existing electron accelerators to study gluon distribution by photon gluon fusion --- isolated via jets or heavy quarks.

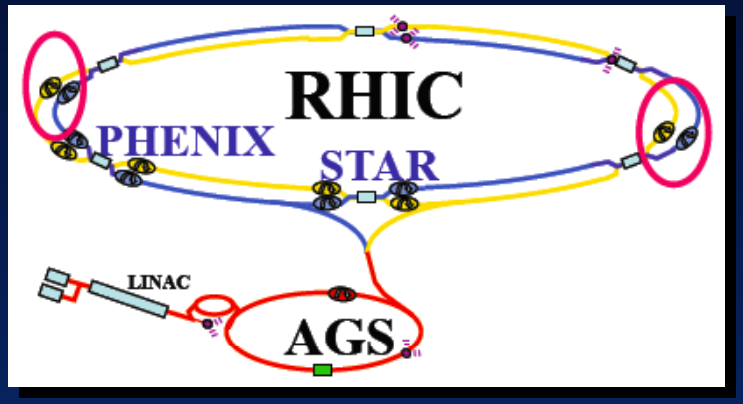
$$\gamma\, g \to q\,\bar{q} \to \text{jet jet}$$

$$\gamma\, g \to c\bar{c}$$

- Intrinsically higher order because gluon must transfer its spin to $q\bar{q}$ pair before virtual photon can interact
- Compromised by low energy (HERMES), spin dilution (COMPASS), and by scale sensitivity due to low Q^2

Gluon spin in the nucleon -- a world class problem

$\overrightarrow{\text{RHIC}}$



A conjunction of good fortune --

- A polarizable collider
- Strong accelerator physics group
- DOE and RIKEN support

Major Japanese Physics & Financial Support

RIKEN BNL Research Center

- Polarized pp - collider -- gluons enter at leading order

$qg \rightarrow q\gamma$ observed as γ + jet

$gg \rightarrow gg$ or $q\bar{q}$

$gq \rightarrow gq$ observed as π^0 + jet

Renaissance in QCD spin physics 1988 -- 2005

$\overrightarrow{\text{RHIC}}$ *** Δg modelling, relation to anomal

$\mathcal{L}_Q$ -- orbital angular momentum and DVCS

$\overrightarrow{\text{RHIC}}$ ** Transversity --- the final leading twist quark distribution

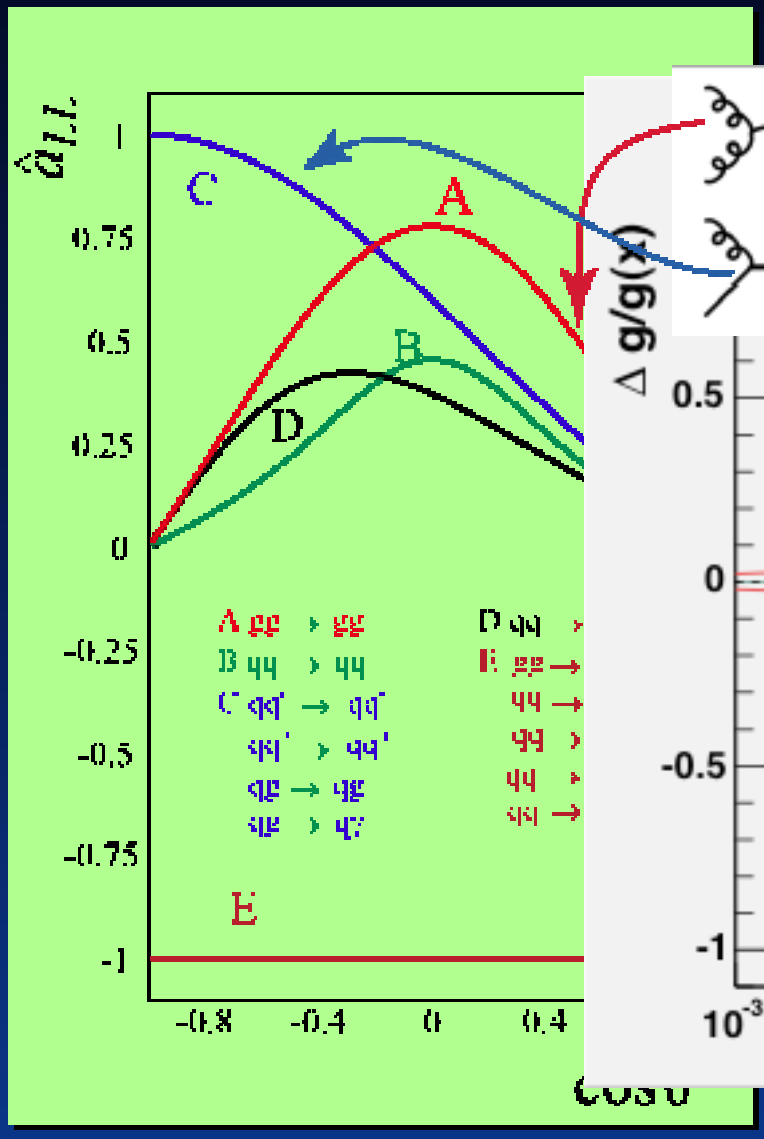
$\overrightarrow{\text{RHIC}}$ ** Flavor decomposition of the quark and antiquark spin $\Delta\bar{u}$, $\Delta\bar{d}$, ...

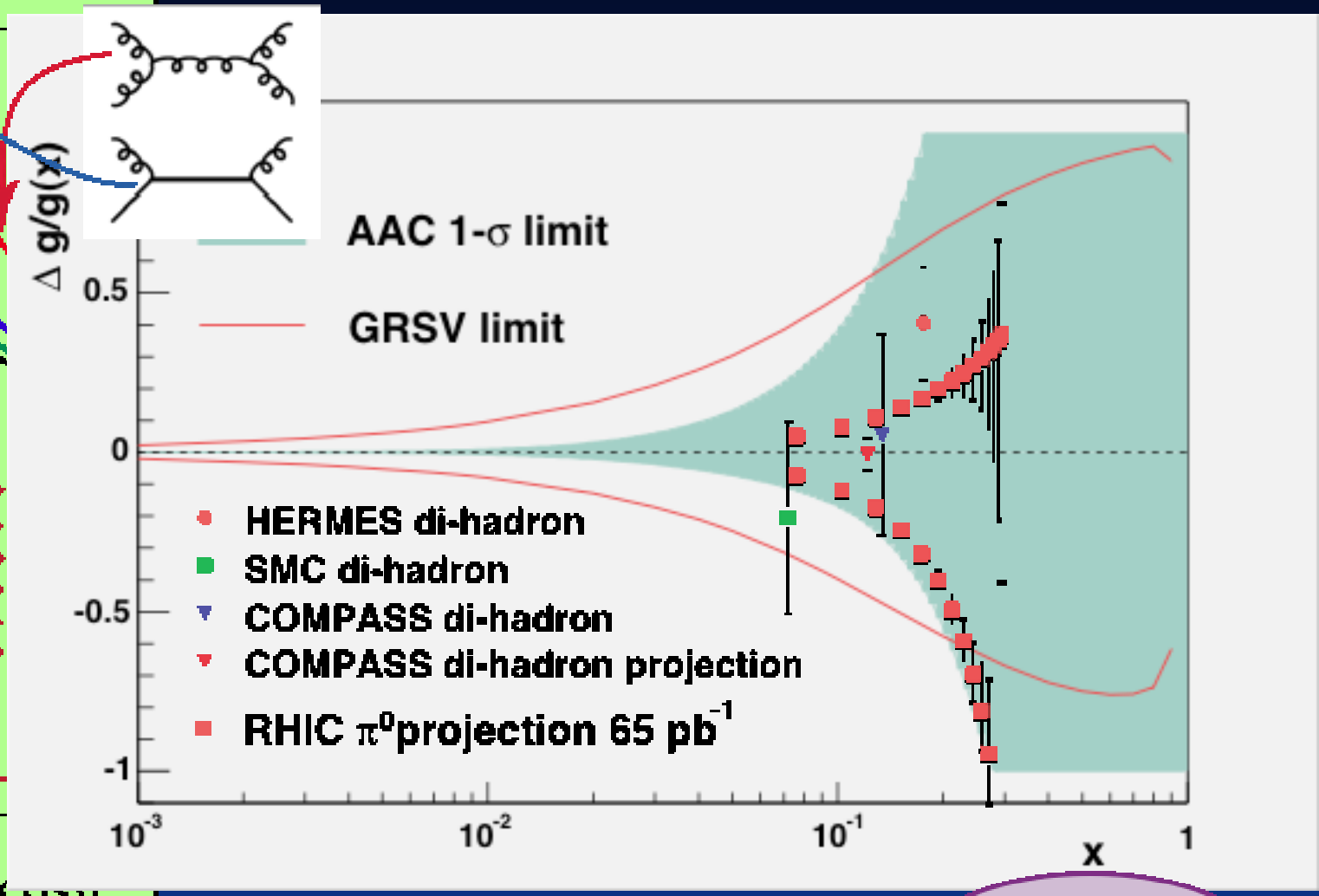
$\overrightarrow{\text{RHIC}}$ *** Absence of gluon transversity

$\overrightarrow{\text{RHIC}}$ *** Single spin asymmetries --- spin/momentum correlations in the nucleon

Example I: Gluon spin distribution at RHIC

π^0 production at $\sqrt{s} = 200$ GeV at PHENIX





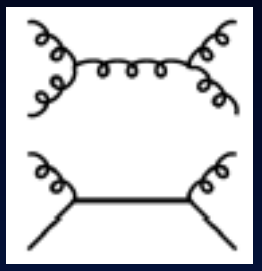
200 GEV
NEAR TERM

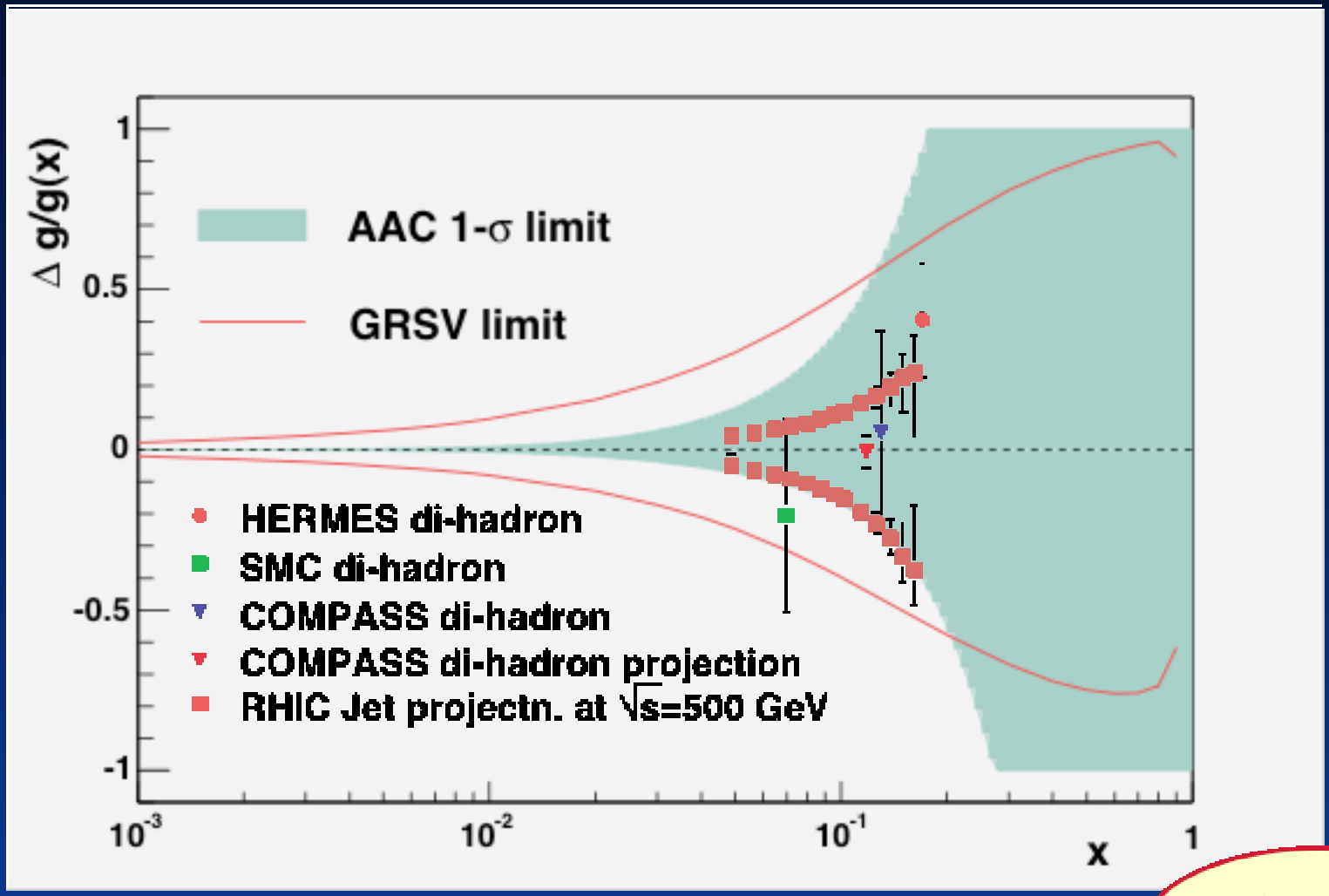
Analyzing power

Sensitivity

Example I continued

Jet production at $\sqrt{s} = 500$ GeV at STAR

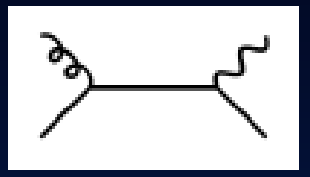


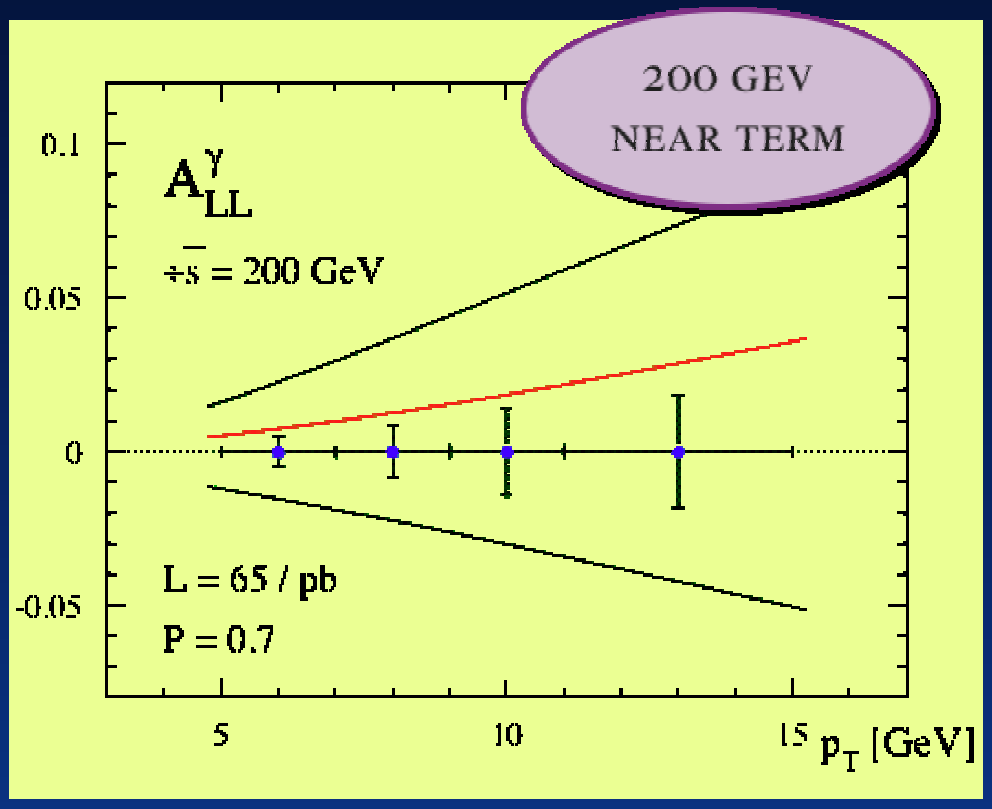


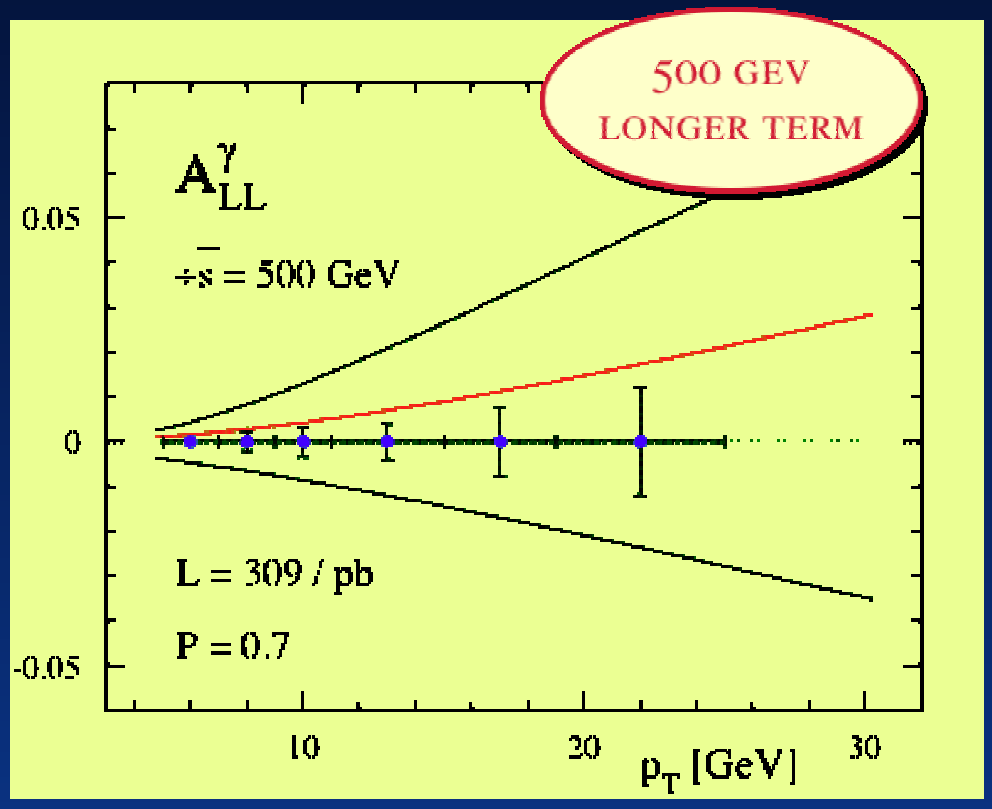
500 GEV
LONGER TERM

Example I continued

Single photon production at PHENIX for
$\sqrt{s}$ = 200 and 500 GeV







$\sqrt{s}$ = 200 GeV L=65 pb^{-1}

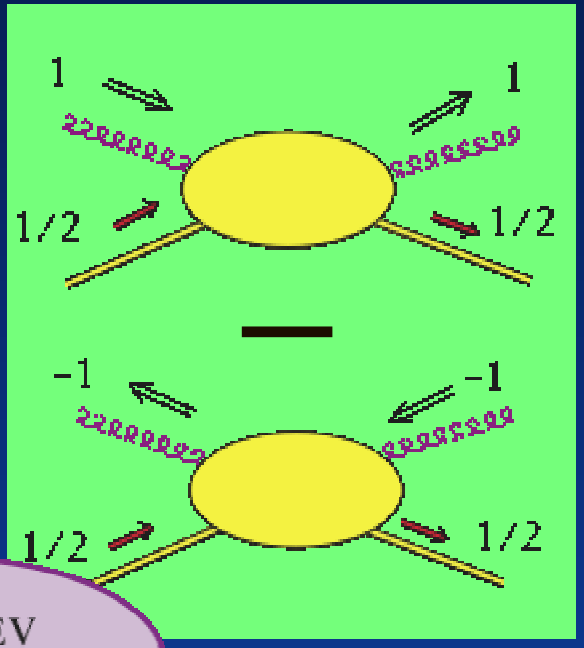
$\sqrt{s}$ = 500 GeV L=309 pb^{-1}

Example II: Absence of gluon transversity

- Relatively easy, novel test of QCD
- Transversity corresponds to helicity flip, which is forbidden for gluons by absence of helicity zero mode -- a consequence of gauge invariance

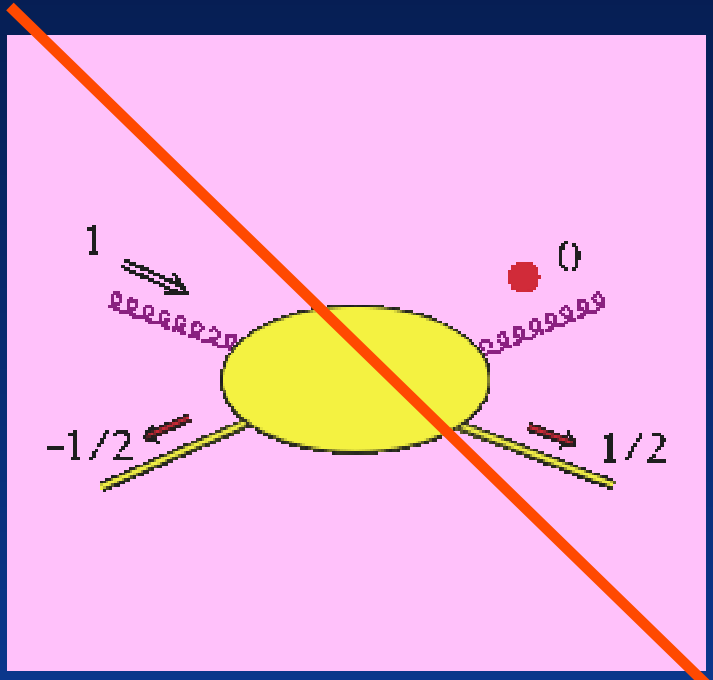
So for any hard process, such as jet or single gamma production

$$\frac{\mathcal{A}_{LL}}{\mathcal{A}_{TT}} \gg 1$$



200 GEV
NEAR TERM

Δg

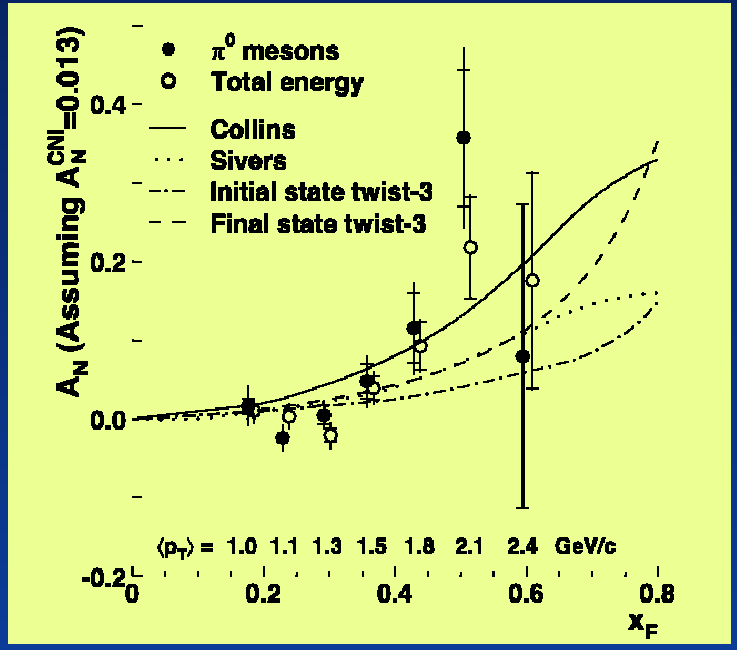


Transversity

Omitted for lack of time

- Flavor separation of quark polarizations using chiral structure of W-production
- Quark transversity measurements through Collins effect and two pion asymmetries
- Single spin asymmetries: Finally making progress on old problem. Large asymmetries have already been observed at RHIC at energies where perturbative QCD can be applied

Two particle correlations offer possibility to unravel QCD spin-momentum correlations in initial and final state (Collins & Sivers)



Conclusions

- Hard QCD spin physics program at RHIC lies at the core of the precision studies in QCD
- Strongly linked to several aspects of national nuclear physics program
- Likely to provide answers to famous, long standing questions (gluon spin) and to frame new questions (single transverse spin asymmetries)
- Program is just now ready to flower
- Important results will come in only a few years of running at 200 GeV
- Plenty more to come at 500 GeV (not to mention eRHIC)